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Rocket Based Combined Cycle (RBCC) Propulsion Technology
Workshop Proceedings Executive Summary

Submitted to

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TECHNOLOGY WORKSHOP. VOLUME 1:
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Rocket-Based Combined-Cycle
Propulsion Technology
Workshop



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Dear Eric,

The following two enclosures in camera ready form constitute the final output delivery as specified in contract number NAS8-38609 D.O. 10:

- o Rocket Based Combined Cycle (RBCC) Propulsion Technology Workshop Proceedings Executive Summary
- o Rocket Based Combined Cycle (RBCC) Propulsion Technology Workshop Proceedings Final Report

I would appreciate a copy of the final distribution list for my records.

It has been a pleasure working with you and we at the Propulsion Research Center are looking forward to future association with you. Your professional guidance in performing this contract is greatly appreciated.

Clark W. Hawk, Ph D PE
Director

Enclosures

cc: with enclosures
Ms Sue Weir
cc without enclosures
RBCC Program Steering Committee

Table of Contents

I. Introduction

A. Mission and Space Transportation Options	1
B. Vehicle Integrated RBCC Propulsion Systems	2
C. RBCC Design, Development and Test Definiation	2
D. Spaceflight Fleet Applications and Operations	2

II. RBCC Propulsion Systems

A. Background of RBCC Propulsion Systems	2
B. RBCC Propulsion System Alternatives	4

III. Findings/Results

A. Vehicle Integrated RBCC Propulsion Systems	5
B. Development Facilities	8
Ground Test	
Flight Test	
C. Vehicle Systems	9
D. Operational Considerations	11

IV. Conclusions/Recommendations

A. Conclusions	12
B. Recommendations	14

I. INTRODUCTION

The goal of the Rocket-Based Combined Cycle (RBCC) Propulsion Technology Workshop was to assess the RBCC propulsion system's viability for Earth-to-Orbit (ETO) transportation systems. This was accomplished by creating a forum (workshop) in which past work in the field of RBCC propulsion systems was reviewed, current technology status was evaluated, and future technology programs in the field of RBCC propulsion systems were postulated, discussed and recommended.

Extensive tutorial activities were accomplished prior to and at the beginning of the workshop. Prior to the workshop, a written tutorial summarizing past work in the field and current relevant research was distributed to workshop participants¹. At the workshop, these tutorial activities were extended and expanded through some twenty-six fifteen minute briefings by specially selected expert presenters. The tutorial activities met two needs. First, since workshop participants came from a variety of technical disciplines, the tutorial activities served to provide necessary knowledge to those participants whose background was not in combined cycle propulsion. Second, since much of the research relevant to RBCC propulsion systems was conducted in the 1960's, the tutorial activities provided a review of past technology programs in the field and informed the participants of technology programs currently underway.

Current technology status was evaluated by four topical breakout groups. Each of the groups was responsible for analyzing a particular aspect of RBCC propulsion systems. A brief description of each group's responsibilities follows.

A. Mission and Space Transportation Options (Group 1)

Breakout Group 1 examined various launch vehicle concepts to determine their suitability for incorporating RBCC propulsion systems and the advantages that RBCC propulsion systems would bring to LEO

¹ Chojnacki, K. and Hawk, C., "A Tutorial for the Rocket Based Combined Cycle Propulsion Workshop," Propulsion Research Center, The University of Alabama in Huntsville, March 1992.

vehicles. In addition, the group determined propulsion system technology drivers for the particular vehicles.

B. Vehicle-Integrated RBCC Propulsion Systems (Group 2)

Breakout Group 2 defined propulsion technology requirements for RBCC powered launch vehicles. The group defined criteria for the time frame of application to guide in defining technologies to be developed. Component development areas addressed were the inlet, combustor, nozzle, materials, propellant feed systems, cooling/thermal protection, fuels, structures and sealing/actuation.

C. RBCC Vehicle Design, Development, and Test Definition (Group 3)

Breakout Group 3 identified required critical technology areas for development, assessed needs in the design methods and tools, and addressed ground and flight test facility requirements relative to operations and design certification.

D. Spaceflight Fleet Applications and Operations (Group 4)

Breakout Group 4 traced the life-cycle of a RBCC powered vehicle from its development phase through its certification and to its operational phase. The group formulated testing approaches, designed a certification process, developed an operations scenario, and discussed life cycle costs.

II. RBCC PROPULSION SYSTEMS

A. Background of RBCC Propulsion Systems

Many of the concepts relevant to RBCC engines were first studied in the mid-1960's by a team led by the Marquardt Corporation which conducted a study on composite (combined-cycle) propulsion systems.² The study objectives were:

² Escher, W.J.D., and Flornes, B.J., 'A Study of Composite Propulsion Systems for Advanced Launch Vehicle Applications,' Final Report on NASA Contract NAS7-377, The Marquardt Corporation, Van Nuys, CA, April 1967.

- 1) To systematically appraise the significance of Rocket-Based Combined Cycle (RBCC) engines to potential advanced launch vehicle missions in the period, post 1975;
- 2) To determine the technology ramifications of RBCC engines with particular emphasis on delineating critical or pacing technology requirements;
- 3) To systematically and comprehensively document technical data which would be useful for further studies involving RBCC engines, with emphasis on vehicle/mission applications.

During the study, Marquardt examined thirty-six candidate engine concepts from which twelve were chosen for further analysis. From these twelve, the two most promising were (for the relatively near and far term, respectively): the Supercharged Ejector Ramjet, and the ScramLACE engines. Details of these systems will be given later.

This study dealt almost exclusively with two-stage-to-orbit (TSTO) systems in which the first stage utilized RBCC propulsion systems and the second stage was all-rocket. The study showed increased performance (payload/TOGW) over all-rocket-powered vehicles for fully recoverable, orbital launch systems. Marquardt determined that the more attractive combined cycle propulsion systems are characterized as ejector or advanced air-augmented rocket systems which are capable of ramjet operation following the initial acceleration phase.

These air-augmented rocket engine concepts (RBCC) were revisited in 1986 in a study focused on the analysis of past work in the field of rocket-based combined cycle engine systems.³ Five RBCC engines were selected for further evaluation and investigation of design approach alternatives which integrate these concepts into a vehicle design. The five RBCC engines selected were: 1) the Ejector Scramjet; 2) the Supercharged Ejector Scramjet; 3) the ScramLACE; 4) the Supercharged ScramLACE; 5) and the Recycled Supercharged ScramLACE.

³ Foster, R., Escher, W.J.D., and Robinson, J., 'Air-Augmented Rocket Propulsion Concepts,' AFAL-TR-88-004, USAF Astronautics Laboratory, Edwards AFB, CA, January 1988.

B. RBCC Propulsion System Alternatives

The Ejector Scramjet (ESJ) (Figure 1) is the simplest design of the five. The other four are variations of this design. The ESJ is designed with variable inlet, fixed combustion geometry and fixed exit geometry. The use of thermal choke in the ramjet mode eliminates the need for physically variable exit geometry which is required to control the inlet shock position.

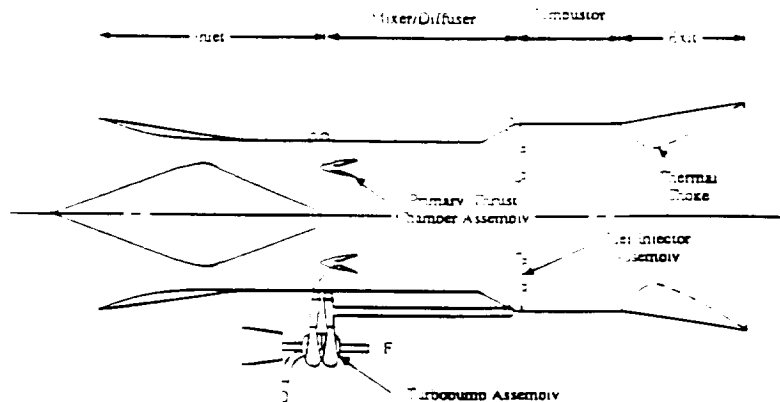


Figure 1: Ejector Scramjet

In the ejector mode, the engine operates at high thrust for liftoff and acceleration to the Mach 2 or 3 range. The rocket primaries are at full thrust using hydrogen/oxygen propellants, and the afterburner is operating at local stoichiometric conditions at full flow. The engine transitions to ramjet mode at about Mach 3 for supersonic to hypersonic acceleration.

In the range of Mach 6-8, the engine transitions to scramjet mode. Hydrogen fuel is injected in the forward part of the duct, now flowing supersonically. Combustion takes place in the constant area and diverging duct sections. Exhaust gas expansion initiates in the nozzle and completes on the aft-body of the vehicle.

At some flight Mach number, depending upon vehicle and mission requirements, the engine transitions to rocket mode with the inlet being physically closed. The rocket primary thrusters operate again on hydrogen/oxygen propellant, and the exhaust gases expand in the divergent portion of the duct and finally on the vehicle aftbody.

As mentioned earlier, the remaining alternatives are variations of the Ejector Scramjet. The ScramLACE is the Ejector Scramjet with the tanked liquid oxygen replaced with liquid air produced during flight. Operation of the air liquefaction system is initiated and liquid air is supplied to the rocket primary thrusters which operate on hydrogen/liquid air throughout the ejector mode. Some tanked liquid oxygen is still required, however, for final rocket mode orbital insertion.

With the addition of a turbofan between the inlet subsonic diffuser and the rocket ejector station, a supercharged version is obtained. The supercharger increases ejector mode specific impulse, and, when operated alone as a high bypass ratio turbofan, enables efficient flyback, landing, and self-ferry modes. Integration of the fan subsystem into the engine is a design challenge. Since the flowpath must be completely clear during scramjet operation, the fan must be stowed out of the flowpath. This requires machinery to implement the changes and effective sealing to protect the fan during scramjet operation.

A disadvantage of the ScramLACE is that it must operate extremely fuel-rich because the hydrogen required to liquefy the air exceeds that needed for operation of the rocket primary thrusters leading to fuel-rich afterburning operation. One solution to this problem is recycling a portion of the excess hydrogen back to the hydrogen tank. Slush hydrogen (a 50/50 mixture of liquid and solid hydrogen) is required to recool the recycled hydrogen. The production of slush hydrogen is emerging as a developed technology due to work being done in support of the NASP Technology Maturation Program.

III. FINDINGS/RESULTS

A. Vehicle-Integrated RBCC Propulsion Systems

Vehicles propelled by RBCC propulsion systems require a degree of vehicle/propulsion system integration that has not been achieved before. The propulsion flow path begins on the vehicle leading edge and extends to the vehicle trailing edge. Therefore, in analyzing the RBCC propulsion system, propulsion system design is intimately linked with vehicle design. For the workshop, discussion was focused on RBCC propulsion systems for use in single-stage conical shaped vehicles, and as the first stage of two-stage (second stage all-rocket)

vehicles with staging in the region around a Mach number of 6 (i.e., no scramjet operation).

Not only is propulsion system/ vehicle integration a key issue, the integration of the propulsion system itself is a significant challenge. As mentioned earlier, the simplest RBCC propulsion system transitions from air-augmented rocket take-off and initial acceleration through ramjet mode to scramjet mode followed by all-rocket mode for orbital insertion. Additionally, there are design alternatives such as a supercharging fan subsystem, an air liquification subsystem, and the use of slush hydrogen that must be considered before final propulsion system selection occurs. The essence of combined cycle propulsion is a single engine assembly capable of operating in various modes. That implies that at least some engine components must be used for more than one of the cycles. A major source of concern (particularly for the single-stage vehicle) is the degree of variable geometry required in these multi-use components. Of particular concern is how to protect the machinery required to implement these geometric changes from the harsh engine environment.

As stated, initial thrust is provided by air-augmented rocket propulsion. The primary issue related to air-augmented rocket operation is the mixing between the internal air stream and the rocket exhaust. The mixing length constitutes a performance loss in terms of drag and additional combustor length and weight (although this may be dictated by the other modes). These losses can be minimized and performance improved via efficient mixing enhancement techniques.

The performance of the propulsion system during scramjet mode is the most critical aspect of engine operation. As mentioned above, the propulsion system flow path includes the entire vehicle body. This is particularly true for the scramjet mode. The vehicle forebody provides initial compression for the engine module inlet. The forebody must be designed to delay laminar to turbulent transition in order to minimize friction drag and boundary layer thickness while providing a uniform flow at entrance to the engine module. Converting the forebody flow properties to acceptable conditions for the combustor component provides the criteria for specifying inlet configuration and configuration variations. Inlets for use on SSTO vehicles require variable geometry to match combustor operating requirements through the various modes and to close for all-rocket

orbital insertion. Transition point prediction, boundary layer separation control, shock/shock interaction, and shock boundary layer interaction must all be considered during inlet design.

The combustor must be designed for high combustion efficiency and maximum energy release. Because of the multiple operating modes of a RBCC propulsion system there are concerns of achieving adequate mixture ratios and the ability to deep throttle the fuel injectors over the broad operating range. Also, at large Mach numbers the fuel injection scheme becomes an issue, as the momentum of the fuel begins to have a much stronger impact on the achievable thrust, dictating an axial injection scheme. The integral rocket is an added feature of the RBCC propulsion system approach, and must work with fuel injection schemes to enhance mixing. Also, cooling of the rocket ejector/fuel injectors is a primary concern that requires innovative new solutions.

The experimental database for hypersonic propulsion system nozzles is particularly limited at Mach numbers above 8 due to the lack of propulsion wind tunnels. The prediction of nozzle performance is essential for accurately evaluating vehicle operation because the thrust vector produced in the nozzle must be controlled in order to control vehicle trajectory and attitude. At high speeds, dissociation losses and flow non-uniformity associated with inlet/combustor operation become design issues. Additionally, for adequate nozzle performance at high speeds, a nozzle design must be implemented that produces excessive base drag at transonic speeds. External burning of hydrogen is a possible solution to this problem and research is currently underway through both ground and flight testing.

Engine materials must be able to survive the broad range of chemical constituents envisioned as products of combustion, differences in the operating cycles of typical RBCC propulsion systems, and the increased presence of water vapor within the engine. For various reasons, such as fuel densification, hydrocarbon fuels have been proposed for some RBCC applications. If hydrocarbon fuels are selected, materials must survive higher radiation heat flux than experienced with hydrogen fuel. A specific set of materials must be defined and fully characterized for these applications.

B. Development Facilities

Ground Tests Facilities

The required wind tunnel facilities can be divided into two categories:

- (a) subscale and/or short duration (pulse type) facilities for research and component technology development.
- (b) fullscale, long duration (1 second to 1 minute) facilities for flight-type engine modules.

While no new facility requirements exist for component testing in the Mach 0-8 range, a requirement does exist for near term technology development facilities in the Mach 8-18 range. The facilities need real gas capability (i.e., true total temperatures and pressures with chemically correct test gas composition), capability to provide hydrogen fuel, and LOX augmentation capability.

For fullscale testing, near term upgrades are needed to existing large scale, long duration, clean air facilities in the Mach 0-6 range. A requirement also exists for large scale, long duration, real gas facilities in the Mach 8-18 range. The only known facility with suitable capabilities in the Mach 10-12 range is the Piston Gasdynamic Unit tunnel at TSNIIMASH in Russia. The estimated cost of applying PGU technology to a new tunnel with even greater range is about \$50 M.

Flight Test Facilities

Propulsion system technical development issues can be experimentally addressed in specialized flight tests utilizing existing and near-term test beds. These test bed vehicles would be powered by their existing propulsion systems with test engine subsystems and test rigs mounted on-board. Some possible test bed vehicles include: the B-747 Shuttle Carrier Aircraft (SCA), the NB-52, the SR-71, ICBM boosters, and the space shuttle. In most cases flight testing can provide a realistic environment in terms of ambient turbulence, humidity, cross winds, etc., and may provide a superior testing approach even at a higher per test cost.

C. Vehicle Systems

Vehicle concepts which were estimated to best utilize RBCC propulsion system alternatives were investigated. Two basic designs were considered: a two-stage-to-orbit (TSTO) vehicle with the first stage powered by RBCC propulsion and an all-rocket second stage, and a single-stage-to-orbit (SSTO) reusable vehicle with RBCC propulsion. These vehicle concepts were compared to other vehicle/propulsion system alternatives to see how the vehicles utilizing RBCC propulsion systems ranked against other systems currently under consideration. Vehicle systems were placed into three IOC groups. An IOC of 2005 was considered near term, 2010 mid-term, and 2015 far-term.

Two vehicle requirements were posed; low polar orbit capability of 10,000 pounds, and a total system capacity of 500,000 pounds to orbit per year. A set of evaluation factors, listed in Table 1, was selected as a means to rank the various propulsion/vehicle systems against these requirements. The vehicle system that best met a particular evaluation factor was given the full score for that factor. All other vehicle systems were then rated relative to that vehicle. A vehicle's final score was the sum of its points for all evaluation factors.

Table 1: Evaluation Factors

Safety	18
Operations and Support	16
Technology Maturity	13
Procurement Costs (Development)	13
Mission Reliability	8
Operational Readiness Availability Responsiveness	8
Margins/Sensitivity	8
Evolutionary Payoff	8
Environmental Impact	8

Vehicle systems that scored relatively poorly when placed in the near term category were pushed back to the mid term category and so forth. Due to its complexity (fan and air liquification subsystems),

the RBCC powered TSTO vehicle was dropped from near-term consideration.

Concept/ Propulsion Cycle	Takeoff/ Landing	Stages	IOC
Beta II, Turbojet/Ramjet booster + SSME powered orbiter	HTHL	2	2005
Subsonic Air-Launched Turboramjet second stage + rocket powered orbiter	HTHL	AL + 2	2005
Near-Term AMLS, SSME derived rockets	VTHL	2	2005
AN-225/Interim Hotol, Air Launched, RD-120 derived Rocket	HTHL	AL + 1	2010
SSTO AMLS, Variable Mixture Ratio Staged Combustion Rocket	VTHL	1	2010
Delta Clipper, Dual-Position Bell Expander Cycle Rocket with Deep Throttle	VTVL	1	2010
Aerospike VTHL, Expander Aerospike Rocket	VTHL	1	2010
Sled-Launched HTHL, Lightweight SSME	HTHL	1	2010
Turboramjet/Scramjet Booster + Rocket Orbiter	HTHL	2	2010
ALES, Air-Liquification/Separation/Collection Booster + Rocket Orbiter	HTHL	2	2010
Sled-Launched Air-turborocket	HTHL	1	2010
Hotol-K, Sled-Launched precooled Air-turborocket	HTHL	1	2010
RBCC, LOX Ejector/Ramjet/Scramjet/Rocket	VTHL	1	2015
Airbreathing (slush) Low-Speed System/Ramjet/Scramjet	HTHL	1	2015
RBCC (slush), LOX Ejector/Ramjet/Scramjet/Rocket	VTHL	1	2015

Figure 2: Candidate Vehicle Concepts/Timeframes

Further, for mid and far term consideration, the single-stage version of an RBCC powered vehicle appears preferable. Its advantages were seen to be: ascent cross range to enhance launch window access capability; powered go-around capability for improved safety; actively cooled structures for enhanced re-entry cross range; and a hypersonic cruise spin-off potential. Therefore, the TSTO vehicle concept utilizing an RBCC propulsion system was dropped from further consideration.

The Mission and Space Transportation Options team determined that the preferred near term concept was a TSTO vehicle with the first stage a turbojet/ramjet combined cycle engine and the second stage all-rocket. This configuration was seen as safer due to less reliance on rocket propulsion and was envisioned to have lower development costs than a rocket-based combined cycle first stage.

The SSTO/RBCC powered vehicle was deferred to the far term. Mission goals for the RBCC propulsion system include: increased thrust/weight at sea level; reduced propulsion system complexity; improved operational compatibility; improved materials (high temperature capability, low density); and improved high end thrust and specific impulse.

D. Operational Considerations

Traditionally, the high payload costs to LEO are dominated by operational costs. For any new vehicle whose major objective is to reduce payload cost to LEO, it is imperative to involve operations and user representatives in the conceptual design phase if one expects to reduce the launch staff (standing army) and minimize expensive facilities. As planned, the Delta Clipper (DC-X) program will test new operational methods in the near future and the results of these tests should be examined prior to conceptual design and incorporated to the maximum extent possible. The following is a list of operational considerations:

- Any new LEO vehicle should contain self-diagnosing and self calibration sensors as well as an autonomous health management system free from ground control.
- The vehicle should be designed to minimize propellant preconditioning and propellant detanking. Payload insertion

capability should be provided just before launch. If a two-stage system is used, each stage should use independent propellant tanking lines to eliminate umbilical between stages. Vehicle flight should not be pilot dependent. If a manned flight is required, an independent crew module should be used for life support and crew safety.

- To enhance system reliability and dependability, all dynamic subsystems should be operated below rated capability. This may provide a measure of system robustness and may reduce operations costs and may increase flight reliability.
- Business considerations must be used to determine the necessity for capital investments at multiple launch or landing sites. To stimulate commercial interest, large fixed costs, large launch staffs and expensive facilities must be avoided.

IV. CONCLUSIONS/RECOMMENDATIONS

Conclusions

1. Initial investigations by workshop participants suggest that the best near-term (IOC 2005) application for a combined-cycle engine is a propulsion system for the booster element of a low risk, fully reusable, TSTO launch vehicle. The combined cycle engine suggested for this role was a turboramjet. The enhancement of the existing "Himate" joint NASA/Air Force study of this type of combined cycle engine for TSTO application, including the addition of an applications assessment, could be an affordable way to broaden NASA's Earth-to-orbit propulsion technology program beyond the realm of pure rocket engines.

2. RBCC propulsion technology development is not dependent upon SSTO for justification. The RBCC powered SSTO vehicle received relatively low ratings during workshop discussions primarily due to a perceived high development risk and potential cost growth. More depth of study with a consistent set of groundrules and assumptions is required to show the benefits of RBCC powered SSTO LEO launch vehicles relative to all rocket powered SSTO LEO launch vehicles. The following two questions need to be answered:

- Is SSTO economically feasible?

- Can advancing RBCC propulsion technology for SSTO LEO launch vehicles ever overcome existing rocket technology for these vehicles?

However, RBCC propulsion systems should not be discounted. TSTO vehicles utilizing RBCC propulsion systems have potential performance advantages over all-rocket systems. Additionally, the applicability of RBCC propulsion systems to TSTO vehicle concepts allows for the evolution of a propulsion system to SSTO capabilities by first applying RBCC engine technologies to TSTO vehicle concepts.

3. Among the most critical unknown factors in RBCC powered SSTO vehicle design is the performance of the scramjet mode at high Mach number. Scramjet performance may degrade with increasing Mach number at a much greater rate than has been conventionally assumed.

4. The integral rocket, unique to RBCC propulsion, requires further technology development. At take-off, mixing and mixing enhancements of the air-augmented rocket mode need development. When the rocket primary thrusters are used for orbital insertion, the transition from scramjet mode to all-rocket mode will result in a rocket chamber design that is outside of the current rocket technology data base. Unknown technology issues associated with the integral rocket include the following:

- Combustion stability
- Injector/plume interaction
- Acoustic environments in the inlet and diffuser region after inlet closure
- Control of mixture ratios during inlet closure while maintaining vehicle thrust, and chamber pressures, and heat fluxes.

5. The development of new testing facilities or the upgrading of existing facilities will be required for the development of RBCC propulsion technology. Facilities will be needed for component technology development and for full scale flight-type engine modules. While no new facility requirements for research and component

technology development for the Mach 0-8 range exist, a high priority requirement exists for the near term research and component technology development test facilities in the Mach 8-18 range. Another high priority requirement exists for near term upgrades to existing large scale, long duration clean air facilities for engine developments in the Mach 0-8 range. Finally, a requirement exists for large scale, long duration, real gas facilities for engine development tests in the Mach 8-18 range.

6. Operational considerations (eliminating the standing army) must play an important role in the design of any new LEO launch vehicle. The initial non-recurring investment required to provide reliability, fault-tolerance, safety, and dependability should not be compromised to "sell" a program; because this comes at the expense of operations efficiency. Traditionally, the costs for high usage systems are dominated by operational expenses (standing army). To reduce life-cycle cost, operations engineers and user representatives must be included early in the vehicle design phase.

7. Launch and recovery operations need to be airline type. The goal should be to minimize ground operations and turn around by using a hangar type facility for planned maintenance or repair actions. The vehicle concept should eliminate or at least minimize hazardous ground operations which increase turn around time due to safety requirements.

Recommendations

1. Conduct a systems-level applications study to quantify the benefits and costs associated with RBCC systems, and to define the desired propulsion system and vehicle technology requirements for LEO launch vehicles. All SSTO and TSTO options using all of the applicable propulsion systems (turbine-based combined cycle, rocket-based combined cycle, airbreathing plus rocket combinations, and all-rocket) must be considered. Such a study should be accomplished as soon as possible. It must be conducted with a consistent set of groundrules and assumptions, and before any major expenditures on a RBCC technology development program occur.

Several design options of the RBCC propulsion system need to be considered. Among them are: liquid air systems (LAIR), slush hydrogen, SSTO vs TSTO, horizontal vs. vertical takeoff, turbomachinery systems to enhance low speed performance, cooling

concepts/thermal protection systems, and axisymmetric vs. 2D inlet/nozzle concepts.

2. Make the NASP technology base available to the R&D community. Extensive RBCC studies, conducted in a NASP information-rich environment, are needed to validate the benefits of RBCC propulsion. Archival data from early hypersonic programs should also be reexamined with an eye towards applying advances in subsystem technology (materials, CFD, controls) to update the results from previous programs.

3. Experimentally determine realistic high Mach number (8 to 18) scramjet performance to be used in future RBCC powered SSTD LEO launch vehicle studies.